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Radiative B Meson Decays into $K\pi\gamma$ and $K\pi\pi\gamma$ Final States

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Abstract

We report observations of radiative B meson decays into the $K^+\pi^-\gamma$ and $K^+\pi^-\pi^+\gamma$ final states. In the $B^0 \to K^+\pi^-\gamma$ channel, we present evidence for decays via an intermediate tensor meson state with a branching fraction of $\mathcal{B}(B^0 \to K_2^*(1430)^0\gamma) = (1.3 \pm 0.5(\text{stat.}) \pm 0.1(\text{syst.})) \times 10^{-5}$. We measure the branching fraction $\mathcal{B}(B^+ \to K^+\pi^-\pi^+\gamma) = (2.4 \pm 0.5(\text{stat.})\,^{+0.4}_{-0.2}(\text{syst.})) \times 10^{-5}$, in which the $B^+ \to K^{*0}\pi^+\gamma$ and $B^+ \to K^+\rho^0\gamma$ channels dominate. The analysis is based on a dataset of 29.4 fb^{-1} recorded by the Belle experiment at the KEKB collider.

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Since the first measurement of the inclusive branching fraction for $B \to X_s\gamma$ by the CLEO collaboration in 1995 [1], the flavor changing neutral current process $b \to s\gamma$ has been used as a sensitive probe to search for physics beyond the Standard Model (SM). In experiments at the $\Upsilon(4S)$, a pseudo-reconstruction technique, in which the X_s state is reconstructed from one kaon and multiple pions, has been the most powerful tool to identify $b \to s\gamma$ events. In order to measure more precisely the inclusive rate, a detailed knowledge of the exclusive final states is required. In addition to the already established $B \to K^*\gamma$ decay [2], there are several known resonances that can contribute to the final state. CLEO has reported evidence for $B \to K_2^*(1430)\gamma$ [3]. Some theoretical predictions for the branching fractions of the exclusive decays can be found in Ref. [4]. Exclusive decays, such as $B \to K_1(1400)\gamma$, can also be used to measure the photon helicity, which may differ from the SM prediction in some new physics models [5].

In this Letter, we report on a search for resonant structures K_X above the K^* mass in radiative B meson decays. The analysis is based on a data sample of 29.4 fb^{-1} (31.9 million $B\bar{B}$ events) recorded by the Belle detector [6] at KEKB [7]. KEKB is an asymmetric energy e^+e^- collider (3.5 GeV on 8 GeV) operated at the $\Upsilon(4S)$ resonance. The Belle detector has a three-layer silicon vertex detector (SVD), 50-layer central drift chamber (CDC), an array of aerogel Cherenkov counters (ACC), time-of-flight scintillation counters (TOF), an electromagnetic calorimeter of CsI(Tl) crystals (ECL).

We select events that contain a high energy photon (γ) with an energy between 1.8 and 3.4 GeV in the $\Upsilon(4S)$ center-of-mass (CM) frame and within the acceptance of the barrel ECL ($33^\circ < \theta_\gamma < 128^\circ$). In order to reduce the background from $\pi^0, \eta \to \gamma\gamma$ decays, we combine the photon candidate with all other photon clusters in the event and reject the candidate if the invariant mass of any pair is within 18 MeV/c^2 (32 MeV/c^2) of the nominal π^0 (η) mass (this condition is referred to as the π^0/η veto).

We search for K_X resonances decaying into two-body ($K^+\pi^-$) and three-body ($K^+\pi^-\pi^+$) final states [8] in the invariant mass (M_{K_X}) range up to 2.4 GeV/c^2. For the $K^+\pi^-$ final state, the range $M_{K_X} < 1.2$ GeV/c^2 is excluded to remove K^* contributions. Charged tracks are required to have CM momenta greater than 200 MeV/c, and to have impact parameters within ± 5 cm of the interaction point along the positron beam axis and within 0.5 cm in the transverse plane. To identify kaon and pion candidates, we use a likelihood ratio that is calculated by combining information from the ACC, TOF, and dE/dx (CDC) systems. We apply a tight selection with an efficiency (pion misidentification rate) of 83% (8%) for charged kaon candidates and a loose selection with an efficiency (kaon misidentification rate) of 97% (28%) for charged pion candidates.

We reconstruct B meson candidates from a photon and a K_X system by forming two independent kinematic variables: the beam constrained mass $M_{\rm bc} \equiv \sqrt{(E^*_{\rm beam}/c^2)^2 - \left(|\vec{p}^{\,*}_{K_X} + \vec{p}^{\,*}_\gamma|/c\right)^2}$ and $\Delta E \equiv E^*_{K_X} + E^*_\gamma - E^*_{\rm beam}$, where $E^*_{\rm beam}$ is the beam energy, and $\vec{p}^{\,*}_\gamma$, E^*_γ, $\vec{p}^{\,*}_{K_X}$, $E^*_{K_X}$ are the momenta and energies of the photon and the K_X system, respectively, calculated in the CM frame. In order to improve the $M_{\rm bc}$ resolution, the photon momentum is rescaled so that $|\vec{p}^{\,*}_\gamma| = (E^*_{\rm beam} - E^*_{K_X})/c$ is satisfied.

The largest source of background originates from continuum $q\bar{q}$ ($q = u, d, s, c$) production. To suppress this background, we use a Fisher discriminant [9] formed from six modified Fox-Wolfram moments [10] and the cosine of the B meson flight direction ($\cos\theta^*_B$). The moments are calculated in the rest frame of the B candidate to avoid a correlation with $M_{\rm bc}$ [11]. Signal and background events are classified according to a likelihood ratio $LR = \mathcal{L}_{\rm sig}/(\mathcal{L}_{\rm sig} + \mathcal{L}_{\rm bg})$, where the likelihood $\mathcal{L}_{\rm sig}$ ($\mathcal{L}_{\rm bg}$) is the product of the probability density functions (PDF)

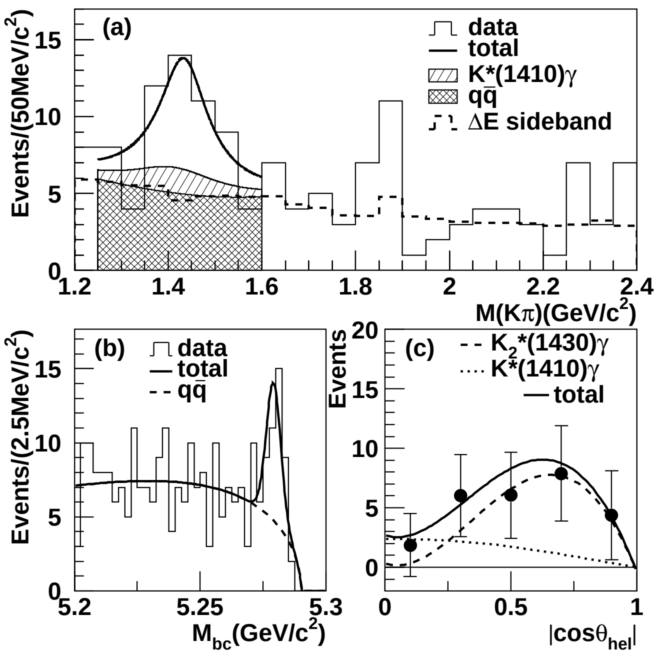

FIG. 1: (a) $M_{K\pi}$ (b) $M_{\rm bc}$ and (c) $|\cos\theta_{\rm hel}|$ distributions for $B^0 \to K^+\pi^-\gamma$ candidates. The unbinned ML fit results are shown in (a) and (c). The $q\bar{q}$ backgrounds are subtracted in (c). $M_{\rm bc} > 5.27$ GeV/c^2 is applied in (a) and (c), and 1.25 GeV/$c^2 < M_{K\pi} < 1.6$ GeV/c^2 is applied in (b) and (c). In (a), ΔE sideband data is scaled to the unbinned ML fit result and overlaid.

of the Fisher discriminant and $\cos\theta^*_B$ for signal (background). The PDFs for the Fisher discriminant are determined from Monte Carlo (MC) simulations. For $\cos\theta^*_B$, we assume a $1-\cos^2\theta^*_B$ behaviour for signal events and a flat distribution for continuum background. The selection criteria on the likelihood ratio are chosen so that $S/\sqrt{S+N}$ is maximized, where S and N are (MC) signal and background yields, respectively. The optimized criteria retain 68% of the $B^0 \to K^+\pi^-\gamma$ signal and 42% of the $B^+ \to K^+\pi^-\pi^+\gamma$ signal.

The B decay signal is separated from background, first by applying a requirement on ΔE and then by fitting the $M_{\rm bc}$ spectrum. If we find multiple candidates with $|\Delta E| < 0.5$ GeV and $M_{\rm bc} > 5.2$ GeV/c^2 in the same event, we take the candidate which gives the highest confidence level when we fit the K_X decay vertex (best candidate selection). We then select candidates with -100 MeV $< \Delta E < 75$ MeV, which removes 19% and 3% of signal on the lower and higher sides, respectively. We define a ΔE sideband to be 100 MeV $< \Delta E <$ 500 MeV at $M_{\rm bc} > 5.2$ GeV/c^2, in which we expect negligible signal contribution.

In the $B^0 \to K^+\pi^-\gamma$ analysis, we obtain the $M_{K\pi}$ distribution shown in Fig. 1(a). We observe an excess around $M_{K\pi} = 1.4$ GeV/c^2 [12]. The $M_{\rm bc}$ distribution with 1.25 GeV/$c^2 <$ $M_{K\pi} < 1.6$ GeV/c^2 is shown in Fig. 1(b). We fit the $M_{\rm bc}$ distribution to extract the signal yield. The distribution for the $q\bar{q}$ background is modeled by an ARGUS function [13] in which the shape is determined from the ΔE data sideband. The distribution for the signal component is modeled by a Gaussian determined from signal MC calibrated by $B^- \to D^0\pi^-$ data. The signal yield is found to be $27\,^{+8}_{-7}$(stat.)$\,^{+1}_{-3}$(syst.) with a statistical significance of 5.0σ. Here, the significance is defined as $\sqrt{-2\ln(\mathcal{L}(0)/\mathcal{L}_{\rm max})}$, where $\mathcal{L}_{\rm max}$ is the maximum of the likelihood and $\mathcal{L}(0)$ is the likelihood for zero signal yield.

The observed signal may be explained as a mixture of three components: $B^0 \to$

$K_2^*(1430)^0\gamma$, $B^0 \to K^*(1410)^0\gamma$ and non-resonant (N.R.) $B^0 \to K^+\pi^-\gamma$. In order to separate these components, we apply an unbinned maximum likelihood (ML) fit to $M_{\rm bc}$, the cosine of the decay helicity angle ($\cos\theta_{\rm hel}$) and $M_{K\pi}$. The expected $\cos\theta_{\rm hel}$ distributions are $\sin^2 2\theta_{\rm hel}$, $\sin^2\theta_{\rm hel}$ and uniform for these three components, respectively. The PDFs for $\cos\theta_{\rm hel}$ and $M_{K\pi}$ are determined from the ΔE sideband data for $q\bar{q}$ background, from the corresponding MC samples for resonant components, and from an inclusive $b \to s\gamma$ MC sample [11] for the non-resonant component. The $\cos\theta_{\rm hel}$ PDFs for signals are distorted up to 20% due to a non-uniform efficiency. The validity of the method is tested with $B^- \to D^0\pi^-$ data and MC.

The fit results for $M_{K\pi}$ and $\cos\theta_{\rm hel}$ are overlaid in Figs. 1(a) and 1(c), and summarized in Table I. We find evidence for radiative decays via an intermediate tensor state, $B^0 \to K_2^*(1430)^0\gamma$. The $K^*(1410)^0\gamma$ and non-resonant components are not significant, so we set upper limits. The 90% confidence level upper limit N is calculated from the relation $\int_0^N \mathcal{L}(n)dn = 0.9\int_0^\infty \mathcal{L}(n)dn$, where $\mathcal{L}(n)$ is the maximum likelihood with the signal yield fixed at n.

We estimate the systematic error due to the fitting procedure as follows. For the signal shapes in the $M_{\rm bc}$ and $M_{K\pi}$ distributions, we vary the mean and width parameters in the fit within their experimental errors. We also test the validity of the background PDFs by replacing them with those obtained from a $q\bar{q}$ MC sample. We assign the largest deviation in these tests as the systematic error of the signal yield.

The event selection efficiency for $B^0 \to K_2^*(1430)^0\gamma$ is (5.0 ± 0.3)% including the sub-decay branching fractions. The error includes contributions from photon detection (2.8%), tracking (2.3% per track), kaon identification (0.6%), pion identification (0.5%), event selection including likelihood ratio, π^0/η veto and best candidate selection (2.0%) and uncertainty of the sub-decay branching fractions (2.4%). Assuming an equal production rate for $B^0\bar{B}^0$ and B^+B^-, this leads to a branching fraction of $B^0 \to K_2^*(1430)^0\gamma$ of $(1.3 \pm 0.5(\text{stat.}) \pm 0.1(\text{syst.})) \times 10^{-5}$.

The result agrees with the predictions based on a relativistic form factor calculation [4]. Our result is also consistent with the CLEO measurement [3] when we neglect the non-resonant component and assume as they did that the $K^*(1410)\gamma$ component is negligible.

In the $B^+ \to K^+\pi^-\pi^+\gamma$ analysis, we find additional background sources from a MC study. Cross feed from $B \to K^*\gamma$ to $B^+ \to K^+\pi^-\pi^+\gamma$ becomes negligible after removing positively identified $B \to K\pi\gamma$ events. The size of the cross feed from other $b \to s\gamma$ decays, especially from those with a π^0 in the final state, is estimated by using the inclusive $b \to s\gamma$ MC sample. The contribution from the $b \to c$ background is estimated by using a corresponding MC sample.

To extract the signal yield, we fit the $M_{\rm bc}$ distribution shown in Fig. 2(a). In addition to a Gaussian and an ARGUS function to describe the signal and $q\bar{q}$ background components obtained using the same method as in the $B \to K\pi\gamma$ analysis, smoothed MC histograms for the $b \to s\gamma$ cross feed and other B meson decays are used to model the $M_{\rm bc}$ shape, where the normalizations are fixed assuming the luminosity and the measured $b \to s\gamma$ branching fraction [11, 16]. We find the signal yield of $57\,^{+12}_{-11}(\text{stat.})\,^{+6}_{-2}(\text{syst.})$ with a 5.9σ statistical significance.

The M_{K_X} distribution is shown in Fig. 2(b), where the distribution for $q\bar{q}$ is obtained from the ΔE sideband and is normalized using the fit result. We observe no signal excess above 1.8 GeV/c^2. The $B^+ \to K^+\pi^-\pi^+\gamma$ signal may be explained as a sum of decays through kaonic resonances such as $B^+ \to K_1(1400)^+\gamma$ and $B^+ \to K^*(1680)^+\gamma$. The current

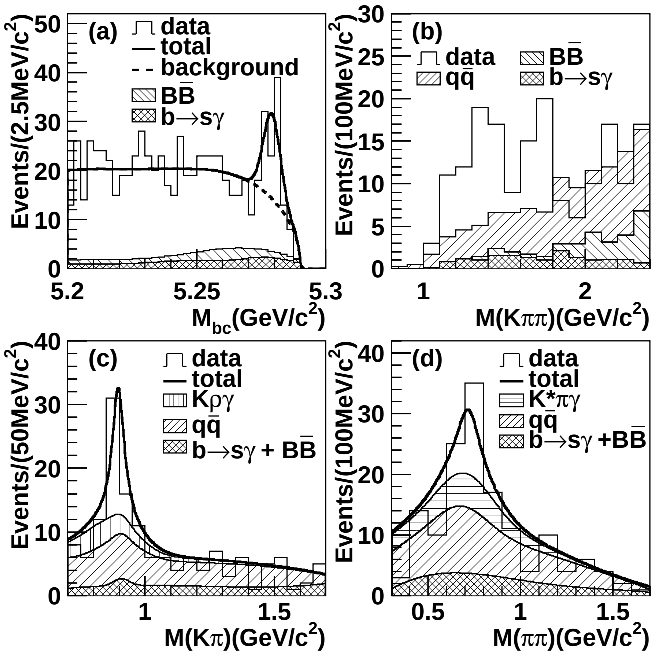

FIG. 2: (a) $M_{\rm bc}$, (b) M_{K_X}, (c) $M_{K\pi}$ and (d) $M_{\pi\pi}$ distributions. The fit result of the $M_{\rm bc}$ distribution is shown in (a), while the result of the unbinned ML fit is shown in (c) and (d). $M_{\rm bc} > 5.27$ GeV/c^2 is applied in (b), (c) and (d).

statistics and the existence of a large number of resonances prevent us from decomposing the resonant substructure. However, it is still possible to measure the $K^*\pi\gamma$ and $K\rho\gamma$ components separately, as most of the resonances have sizable decay rates through the $K^*\pi$ and $K\rho$ channels.

To find the composition of the signal, we perform an unbinned ML fit to $M_{\rm bc}$, $M_{K\pi}$ and $M_{\pi\pi}$ with three signal components ($K^*\pi\gamma$, $K\rho\gamma$ and non-resonant $K\pi\pi\gamma$) and a $q\bar{q}$ background component. In addition, the components from $b \to s\gamma$ cross feed and from other B meson decays are included in the fit with fixed normalizations. The $M_{K\pi}$ and $M_{\pi\pi}$ shapes for the $q\bar{q}$ background are determined from the ΔE sideband data, and those for the other components are determined from the corresponding MC samples.

In order to model the signal PDF for the $K^*\pi\gamma$ component, we use a mixture of $B^+ \to K_1(1400)^+\gamma \to K^{*0}\pi^+\gamma$ and $B^+ \to K^*(1680)^+\gamma \to K^{*0}\pi^+\gamma$ MC. The $K_1(1400)\gamma$ fraction of the mixture is determined to be 0.74 ± 0.14 by examining a background-subtracted $M_{K\pi\pi}$ distribution for candidates with $|M_{K\pi} - M_{K^*}| < 75$ MeV/c^2 (K^* mass cut). Likewise for the $K\rho\gamma$ PDF, a mixture of $B^+ \to K_1(1270)^+\gamma \to K^+\rho^0\gamma$ and $B^+ \to K^*(1680)^+\gamma \to K^+\rho^0\gamma$ MC is used, where the $K_1(1270)\gamma$ fraction is determined to be 0.68 ± 0.17 according to a background-subtracted $M_{K\pi\pi}$ distribution for candidates with $|M_{\pi\pi} - M_\rho| < 250$ MeV/c^2 and $|M_{K\pi} - M_{K^*}| > 125$ MeV/c^2 (ρ mass cut).

Figures 2(c) and 2(d) show the distributions and fit results for $M_{K\pi}$ and $M_{\pi\pi}$. The selection efficiency is estimated from a MC sample with the mixture of resonances used for the PDF determination. We also consider other well-established resonances [14] which give slightly different efficiencies, and assign the difference in the result as a systematic error. The signal yields, efficiencies and the branching fractions are listed in Table I. The total $B^+ \to K^+\pi^-\pi^+\gamma$ branching fraction is dominated by $B^+ \to K^{*0}\pi^+\gamma$ and $B^+ \to K^+\rho^0\gamma$; the

TABLE I: Measured signal yields, statistical significances, reconstruction efficiencies, branching fractions ($\mathcal{B}$) and 90% confidence level upper limits (UL) including systematic errors. The first and second errors are statistical and systematic, respectively. Efficiencies include the sub-decay branching fractions [15]. Efficiencies for $K^+\pi^-\gamma$ and $K^+\pi^-\pi^+\gamma$ are based on a mixture of the measured sub-components.

Mode	Signal Yield	UL(yield)	Significance	Efficiency(%)	$\mathcal{B}$ ($\times 10^{-5}$)	UL ($\times 10^{-5}$)
$K^+\pi^-\gamma$ †	$27\,^{+8}_{-7}\,^{+1}_{-3}$	—	5.0 §	18 ± 2	$0.46\,^{+0.13}_{-0.12}\,^{+0.05}_{-0.07}$	—
$K_2^*(1430)^0\gamma$	$21\,^{+8}_{-7}\,^{+0}_{-1}$	—	3.2	5.0 ± 0.3	$1.3 \pm 0.5 \pm 0.1$	—
$K^*(1410)^0\gamma$	$7.7\,^{+7.1}_{-5.7}\,^{+0.5}_{-1.3}$	19	—	0.58 ± 0.12	—	13
$K^+\pi^-\gamma$ (N.R.) †	$0.0\,^{+4.6}_{-0.0} \pm 0.0$	15	—	19 ± 1	—	0.26
$K^+\pi^-\pi^+\gamma$ ‡	$57\,^{+12}_{-11}\,^{+6}_{-2}$	—	5.9 §	7.5 ± 0.7	$2.4 \pm 0.5\,^{+0.4}_{-0.2}$	—
$K^{*0}\pi^+\gamma$ ‡	$33\,^{+11}_{-10} \pm 2$	—	3.7	5.0 ± 0.5	$2.0\,^{+0.7}_{-0.6} \pm 0.2$	—
$K^+\rho^0\gamma$ ‡	$24 \pm 12\,^{+4}_{-7}$	43	2.2	7.4 ± 0.7	$1.0 \pm 0.5\,^{+0.2}_{-0.3}$	2.0
$K^+\pi^-\pi^+\gamma$ (N.R.) ‡	$0\,^{+11}_{-0} \pm 0$	20	—	7.6 ± 0.7	—	0.92
$K_1(1270)^+\gamma$	$4.0 \pm 2.4 \pm 0.6$	10	—	0.40 ± 0.08	—	9.9
$K_1(1400)^+\gamma$	$26 \pm 6\,^{+2}_{-0}$	36	—	2.6 ± 0.3	—	5.0

† $1.25\ \mathrm{GeV}/c^2 < M_{K\pi} < 1.6\ \mathrm{GeV}/c^2$ ‡ $M_{K\pi\pi} < 2.4\ \mathrm{GeV}/c^2$ § $M_{\rm bc}$ fit result

statistical significance for the sum of the two is calculated to be 6.2σ and the non-resonant component is consistent with zero. We find evidence for the decay $B^+ \to K^{*0}\pi^+\gamma$ with a 3.7σ significance, while the $B^+ \to K^+\rho^0\gamma$ channel alone yields only 2.2σ. Systematic errors are evaluated using the same procedures as in the $B \to K\pi\gamma$ analysis.

We also search for resonant decays by applying further kinematical requirements. We search for $B^+ \to K_1(1270)^+\gamma$ in the $K^+\rho^0\gamma$ final state by applying the ρ mass cut and $|M_{K_X} - M_{K_1(1270)}| < 100\ \mathrm{MeV}/c^2$. We find 6 candidates with a background expectation of 2.0 ± 0.6 events. To find $B^+ \to K_1(1400)^+\gamma$ in the $K^{*0}\pi^+\gamma$ final state, we apply the K^* mass cut and $|M_{K_X} - M_{K_1(1400)}| < 200\ \mathrm{MeV}/c^2$. We obtain a sizable signal; however we only provide upper limits due to a lack of ability to distinguish these resonances. The results are also listed in Table I.

In conclusion, we have studied radiative B decays with the $K^+\pi^-\gamma$ and $K^+\pi^-\pi^+\gamma$ final states. For $K^+\pi^-\gamma$, we consider $B^0 \to K_2^*(1430)^0\gamma$, $B^0 \to K^*(1410)^0\gamma$ and non-resonant components, and find that only the first one is significant. For $B^+ \to K^+\pi^-\pi^+\gamma$, we observe the decay mode and measure the branching fraction. The branching fractions for $B \to K^*\pi\gamma$ and $K\rho\gamma$ are consistent with the sum of predicted rates of resonant decays [4]. As listed in Table II, we find $(35 \pm 8)\%$ of the total $B \to X_s\gamma$ decay is accounted for by the $B \to K^*\gamma$, $B \to K_2^*(1430)\gamma$, and $B \to K\pi\pi\gamma$ final states.

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TABLE II: Exclusive and inclusive branching fractions for the $b \to s\gamma$ process. Equal branching fractions are assumed for neutral and charged B decays. Using isospin, the branching fraction of $B^+ \to K^{*+}\pi^0\gamma$ ($K^0\rho^+\gamma$) is assumed to be half (twice) of that for $B^+ \to K^{*0}\pi^+\gamma$ ($K^+\rho^0\gamma$).

Mode	$\mathcal{B}$ ($\times 10^{-5}$)	Ref.
$B \to K^*\gamma$	4.2 ± 0.4	[3, 17]
$B \to K_2^*(1430)\gamma$ (excluding $K^*\pi\gamma, K\rho\gamma$)	0.9 ± 0.3	
$B \to K^*\pi\gamma$	3.1 ± 1.0	
$B \to K\rho\gamma$	3.0 ± 1.6	
Sum of exclusive modes	11.2 ± 2.1	
$B \to X_s\gamma$ (inclusive)	32.2 ± 4.0	[11, 16]

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